Atmospheric Multiple Scattering Effects on GLAS Altimetry.

Part II: Analysis of Expected Errors in Antarctic Altitude Measurements

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ABSTRACT

The altimetry bias in GLAS (Geoscience Laser Altimeter System) or other laser altimeters resulting from atmospheric multiple scattering is studied in relationship to current knowledge of cloud properties over the Antarctic Plateau. Estimates of seasonal and interannual changes in the bias are presented. Results show the bias in altitude from multiple scattering in clouds would be a significant error source without correction. The selective use of low optical depth clouds or cloud-free observations, as well as improved analysis of the return pulse such as by the Gaussian method used here, are necessary to minimize the surface altitude errors. The magnitude of the bias is affected by variations in cloud height, cloud effective particle size and optical depth. Interannual variations in these properties as well as in cloud cover fraction could lead to significant year-to-year variations in the altitude bias. Although cloud-free observations reduce biases in surface elevation measurements from space, over Antarctica these may often include near-surface blowing snow, also a source of scattering-induced delay. With careful selection and analysis of data, laser altimetry specifications can be met.

1. Introduction

With increasing concern over warming of the earth's surface the need to develop and implement sound monitoring programs to detect potential large-scale climate changes at an early stage has also grown. The marginal ice zones around the polar ice shelves have been a particular focus of such programs, in the expectation that the early signs of global climate change will be observed here. This view has been bolstered by measurements of significant surface temperature changes in recent decades, especially in the coastal Antarctic [1].

A major goal of the orbital Geoscience Laser Altimeter System (GLAS) is to measure and monitor a particular aspect of climate change in the high latitudes, namely changes in the mass balance of the Earth's large ice sheets which are concentrated in the polar regions. Global warming could potentially alter the mass balance of these ice sheets, in turn leading to other climatic changes, notably a possible change in sea level. GLAS proposes to measure inter-annual changes in the thickness of polar ice sheets, and will provide the first estimates of continent-wide elevation changes in the Antarctic and Greenland ice sheets [2].

The determination of ice-sheet mass balance is limited by typical methods, which rely on a comparison of two large numbers - total snow accumulation and total ice loss - that are each subject to large errors. Recently, more accurate methods to measure the ice-sheet mass balance have been developed using repeated altimetry measurements of the ice sheets by airborne lidar [3] and satellite radar [4]. These new methods each contain drawbacks; radar measurements are sensitive to surface slope errors and radar penetration into snow, and relatively few airborne lidar measurements over Greenland and Antarctica have ever been attempted. GLAS measurements will mark an improvement on existing observations, and will record temporal changes in the thickness of the Earth's polar ice sheets from space.

GLAS is a laser-based surface altimeter and atmospheric profiler scheduled to be launched in 2002 as part of the Earth Observing System (EOS) program. For the surface altimetry measurements, the mean elevation of the laser's surface spot will be estimated from a centroid of the return pulse. To permit the determination of mass balance changes, individual ice-sheet altitude measurements must be made with uncertainties smaller than 10 cm. A number of factors affect the accuracy of the altitude measurement, including surface slope, atmospheric propagation and signal noise. A cross-over technique that averages the elevation differences at selected points on the ice sheets is designed to reduce errors in order to measure regional ice elevation changes to an accuracy of 1.5 cm per year, the stated goal of the ice-sheet altimetry [5].

In Part I of this paper ([6] hereafter referred to as DSE), the authors presented calculations of path delays by cloud and aerosol scattering from an analytic double-scattering model and Monte Carlo simulations of lidar surface returns. Both methods demonstrated that multiple scattering by optically thin polar clouds could seriously bias the altitude ranging of GLAS. For example, if the surface height were measured from the centroid of the return pulse, a thin arctic stratus cloud with an optical depth of 0.5, a mean particle radius of 6 microns, and a thickness of 3 km would produce a to-and-fro path delay of 30 cm, corresponding to an altitude bias of 15 cm.

Since the effect of multiple scattering is to always introduce a delay, the mean height change will be affected by the changes in cloud and aerosol layers in the atmosphere. If not corrected, seasonal and annual variation in cloud properties could significantly affect the determination of changes in the surface height. Surface altimetry is a primary objective of the GLAS mission, and multiple-scattering induced delay in the observations has the potential to seriously undermine this goal. Using current knowledge of Antarctic cloud properties, we study the impact of multiple-scattering on the determination of surface altitude, as well as on the interannual variability of it. The use of the atmospheric lidar signals of GLAS to eliminate such errors will also be discussed.

2. Variability of Cloud Properties on the Antarctic Plateau

The purpose of ice-sheet altitude observations is to measure temporal changes in ice thickness. A ranging bias would not be a problem if polar cloud properties were constant over time. Therefore, the critical issue is to determine the potential bias effect from seasonal and interannual variability of cloud properties. DSE found that several cloud parameters can affect the magnitude of multiple scattering-induced delays, including cloud optical depth, cloud particle size, and mean cloud height. The variability in each is now considered in turn.

2.1. Cloud Occurrence

Due to the harsh conditions in the Arctic and Antarctic, as well as their remoteness, observations of polar cloud properties have been far fewer than elsewhere. Even the most comprehensive cloud surveys such as Hahn *et al*. contain only sparse cloud data from the ice sheets over Greenland and Antarctica [7]. Despite this, some estimates of polar cloud characteristics can be made from current knowledge of polar cloudiness. The surveys of Hahn *et al*., for example, summarize surface observations of clouds across the globe. The observations indicate spatial variations over the poles. They are summarized from routine surface observations of sky conditions made by observers at various weather stations around the world. Mean annual values of Arctic cloud occurrence - which records the presence of clouds regardless of the fraction of the sky filled by them - from Hahn *et al*. are shown in Figure 1. The values are typically between 70 and 80 percent, with values greater than 80% in the area around Spitsbergen, and smaller amounts (between 55 and 70 percent) over western Greenland and northern Canada.

Most surface observations of clouds over Antarctica are from coastal stations which report the presence of clouds between 70 to 80 percent of the time, while the few stations located in the interior of the continent report fewer occurrences of clouds, typically seen in between 40 and 60 percent of the observations. The mean annual frequency of clear sky observations in the Arctic Ocean and the coastal stations of Antarctica is usually less than 10 percent [8]. Observations of entirely clear skies are rare at the high latitudes; even stable surface temperature inversions under clear skies usually lead to the formation of near-surface ice crystals, known as diamond dust.

Cloud occurrence varies seasonally over the poles. Hahn *et al*. find that in winter, observations of clouds over most of the Arctic Ocean ranges from 50 to 70 percent. Arctic cloud occurrence is generally higher during the summer, when values range from 65 percent of the observations over western Greenland to over 80 percent of observations in the Siberian Arctic. A similar seasonal cycle occurs over Antarctica, with higher values during the summer, and lower values during the winter. At coastal Antarctic stations, however, clouds are seen far more frequently than over the high plateau. Mean wintertime cloud occurrence over the South Pole ranges from 30 to 40 percent, while in the summer, clouds are observed in 45 to 70 percent of the observations. On the other hand, observations between 1971 and 1980 at the coastal Syowa Station (69 S, 39 E) show a maximum in the late summer, when nearly 80 percent of observations are of clouds, and minima in the early summer (53%) and winter (60%) [9].

Hahn *et al*. also determined the interannual variation (IAV) in cloud occurrences over the poles. IAV was defined as the standard deviation in seasonal cloud occurrence for the period from 1982-1991. The interannual variation in June-July-August (JJA) cloud occurrence for land stations in the Arctic was usually near 5 percent, and was near 10 percent for December-January-February (DJF) observations. Wintertime observations over the Arctic Ocean show IAV values from 20 percent north of Alaska to 2 percent over Spitsbergen. During the summertime the standard deviations ranged from 2 to 5 percent. The interannual variations at the Antarctic coastal stations and at the South Pole are generally near 5 percent.

The most recent year-long study of clouds over the Antarctic plateau is that of Mahesh *et al.* (2001, in press, [10,11]). From ground based longwave spectral observations of clouds at South Pole station in 1992, the authors obtained an annual cycle of cloud base heights, particle effective radii and optical thicknesses. This study was not specifically designed to quantify cloud occurrence throughout the year; their spectrometer had a limited field of view, and observations were made at three viewing zenith angles - 45^{o}, 60^{o}, and 75^{o}- throughout the year to consistently record clouds in the same viewing direction. Mahesh *et al* found clouds in approximately 43% of their spectral observations, roughly consistent with Hahn *et al*.'s multi-year average.

2.2. Cloud height and optical depth

Over much of the Antarctic plateau, surface-based visual estimates of cloud height are constrained by the relative absence of topographical reference points. Mahesh *et al*. use a modified version of the CO_2-slicing method to determine the base height of clouds, from longwave spectral observations. The cloud bases have a bimodal distribution, with the primary maximum in the surface-based inversion layer, and a seasonally dependent secondary maximum between 2.0 and 2.5 kilometers. The higher clouds, i.e. most of the clouds with bases in the 2.0 - 2.5 km range have smaller optical depths (less than 1), whereas clouds with bases near the surface are often thicker, although many of these too have optical depths of less than 2.

Ice crystal precipitation can have a wide range of optical depths, but it is commonly much thicker during the winter. Wilson *et al*. report wintertime observations of ice crystal optical depths between 2.7 and 10.7, although thicknesses as large as 21 have been measured [12]. In the Arctic springtime, the observed thicknesses ranged from 0.015 to 1.9. Mahesh *et al*.'s findings of cloud optical depths confirmed the generally held view that clouds over the Antarctic plateau are optically much thinner than those at the coasts of the continent. Nearly 95% of the clouds at South Pole station were seen to have optical depths smaller than 5.

2.3. Cloud particle size

The multiple-scattering induced path delays will also depend on the microphysical properties of the clouds. Curry *et al*. report that the most comprehensive measurements of wintertime Arctic ice crystal distributions show modal radii between 10 to 80 µm, and an average effective radius of 40 µm [8]. Summertime Arctic stratus, on the other hand, have much smaller mean radii, ranging from 2 to 7 microns.

In the Antarctic, Smiley *et al*. reported that the most common sizes of clear-sky ice crystal precipitation observed during the wintertime are between 50 and 200 microns [13]. However, crystals smaller than 50 microns could not be reliably measured on their particle replicator, and smaller particles were not reported. Stone inferred cloud properties of Antarctic clouds during the wintertime from radiometric profile measurements, and estimated most clouds are optically thin and composed of small particle sizes on the order of 4 to 16 microns [14]. Lubin and Harper retrieved cloud particle sizes using AVHRR infrared radiances, and estimated that the mean summer and winter effective radii over the South Pole are 12.3 and 5.6 µm, respectively [15]. Mahesh *et al*. determined cloud particle effective radii from their 1992 data, and obtained a median particle size of 15 µm; in their study, the effective radii of particles larger than 25 microns could not be accurately determined, and only a lower limit to those particles is given. A particular seasonal pattern observed here indicated that cloud particle sizes in winter mostly ranged between 10 and 20 µm, whereas in summer larger particles, with effective radii larger than 25 µm, were dominant [10,11].

3. Results

3.1. Altitude bias

The observations summarized in Section 2 indicate some variability in polar cloud properties that would lead to seasonal and interannual variation in the altitude bias. To estimate the mean altitude bias for a particular period, the Monte Carlo path delay results from DSE can be weighted by the climatological frequency of various cloud types.

The mean altitude bias for a given period is defined as:

$$\bar{B} = \frac{\Sigma_i \Sigma_j \Sigma_k \cdot b(\tau_i, h_j, r_k) \cdot F_T(\tau_i, h_j, r_k)}{(1 - F) + \Sigma_i \Sigma_j \Sigma_k \cdot F_T(\tau_i, h_j, r_k)}$$

where $b(\tau_i,h_j,r_k)$ is the computed altitude bias for each transmissive cloud based on cloud optical thickness τ, cloud height h, and cloud particle size r, and $F_T(\tau_i,h_j,r_k)$ is the cloud coverage fraction as a function of those same variables for each transmissive cloud. F is the overall cloud cover fraction, τ_i is the distribution of cloud optical depths, h_j is the distribution of cloud heights, and r_k is the distribution of cloud particle sizes. Altitude biases thus obtained can be examined for seasonal or interannual variation, computed as the difference between the mean bias from one season (year) to the next:

In this paper, we obtain altitude bias estimates from Monte Carlo calculations using cloud properties reported by Mahesh *et al.*; these include the frequency of cloud observations, optical depths (τ), cloud heights (h) and cloud effective particle radii (r) derived from infrared spectral measurements made from the ground in 1992. Following equation (1), an altitude bias can be computed for each measurement using these properties, and mean altitude biases over different seasons as well as the entire year can be obtained. Due to interannual variability, GLAS will record cloud conditions over the Antarctic Plateau that are not identical with those from 1992; nevertheless these data represent the best combination of several cloud properties relevant to multiple-scattering induced delay from a single observation program; also, at this time Mahesh *et al*.'s findings remain the only available year-long dataset of cloud properties over the plateau.

Not all clouds will contribute to the altitude bias; optically thick clouds will not be penetrated by the GLAS lidar, and no surface elevation measurements will be made in such cases. According to the specifications of the GLAS mission, clouds with a two-way transmissivity of less than 0.25 would not included in any altimetry estimates. For the geometry of the GLAS lidar, the Monte Carlo calculations by DSE show that when forward scattering is considered the optical depth limit corresponding to the above transmissivity is as large as 2. The optical depths obtained by Mahesh *et al*. at South Pole suggest that this upper limit still permits the use of nearly 75% of the clouds observed during the year. Also, one might minimize altitude biases by using only those measurements made during cloud-free conditions or through optically thin clouds, as shown later in a later section. This will permit more accurate altimetry. However, in such an approach the lower threshold of cloud optical depth eliminates greater numbers of the observations from consideration.

Figure 2 shows the scattering-induced altitude biases expected in GLAS measurements using sky conditions recorded by the interferometer in 1992; histograms are plotted for all observations (2a) as well as for the cloudy cases alone (2b). The large peak of observations with little or no scattering-induced bias in Figure 2a is primarily due to observations of clear-sky, which comprise 57% of the measurements, the remainder are from clouds whose scattering effect is minimal. For the clear-sky observations, it was assumed that the scattering-induced bias is zero, this is explored further in a later section.

Using cloud properties obtained by Mahesh *et al.*, Monte Carlo calculations were performed to obtain the altitude bias that would result, from each combination of cloud height, particle radius and optical depth. Consistent with indications from radiosonde data taken during the year, a typical cloud thickness of 1 km was used in the modeling.

Mahesh *et al*. determined only a lower bound in particle radius in a number of summer-time cases. Also, in a few mostly winter cases of thick clouds only a lower limit to the optical depth was determined. The Monte Carlo calculations used to obtain the values in Figure 2 were run only for those observations of clouds (approximately three-fourths of the total number of clouds observed) in which both particle radius and optical depth were known, i.e. if only a lower limit to either particle size or optical depth is available those clouds are omitted in Figure 2. These omitted values, however, are shown in Figure 3, and are specifically indicated as those with only a lower limit to optical depth (diamonds), those with only a lower limit to particle size (open circles) and those with only a lower limit to both particle radii and optical depths (filled circles) known. In these special cases, it must be assumed that the altitude bias corresponding to scattering-induced delay is at least as large as indicated in Figure 3. The median value of the altitude bias for the entire year, from only the cloud observations, is 10.8 cm, and the mean is 16.2 cm.

For a given value of the optical depth, the bias in altitude will change due to variations in both particle size and in the height of the cloud above the surface. Low clouds scatter photons which, despite the scattered path, still remain within the field of view of the instrument. Scattering by higher clouds, which are more common in the non-winter months (October-March), tends to remove the scattered path lengths from the field of view, thereby biasing the altitude less. With increasing particle radius, however, a cloud of a given optical depth will bias the altitude increasingly, until a limiting particle size is reached at which value the variation in the forward scattering peak is small. The winter altitude biases in Table 3 (discussed in a later section) are smaller than non-winter values; this suggests that the effect of particle sizes in the non-winter months is more significant than the fact that in winter, clouds occur nearer the surface.

3.2. Variability in altitude bias.

If the altitude bias were invariant from one year to another, errors introduced into altimetry measurements as a result of multiple scattering could be neglected, since the objective, namely to determine interannual changes in elevation, could still be fulfilled. However, since the properties of clouds which cause delay by multiple scattering are not constant from one year to the next, the bias varies as well. The interannual variability in bias can result from changes in frequencies of cloud occurrence as well as the fractional cloud cover. More significantly, the bias values are sensitive to changes in the specific microphysical and radiative properties of clouds from one year to the next.

We examine the interannual variability in altitude bias using two different approaches to understand the impact of these different variables. In the first method, we use cloud properties obtained from the spectral measurements of Mahesh *et al*. to obtain altitude biases that would result from such clouds. The variability in the estimated biases is then obtained using the inter-annual variability in cloud occurrence reported by Hahn *et al*. In the second approach, we obtain from routine synoptic reports the averages of the *fraction* of the sky covered by clouds during 1992-94, and the interannual bias changes that would result from variations in the cloud fractions. The former approach considers changes that result from having more (or fewer) clouds from one year to the next, whereas the latter deals with having more (or less) of the sky covered by clouds when they are present.

3.2.1 Variability from spectral observations

To estimate the uncertainty in altimetry from one year of GLAS observations to the next we may consider the average as well as the extremes of variability in cloud occurrence over the Antarctic plateau. The average interannual variation in summer cloud occurrence at the South Pole from Hahn *et al*. is about 5 percent, while it is 11 percent during the winter. To assess the impact of this variation on altimetry measurements, we must additionally know the variation in their optical thicknesses, particle sizes, and the clouds heights. If in any given year the additional (or fewer) clouds seen are negligibly different in their average properties than those seen in the 1992 dataset, then we may well see no change in the annual average altitude bias using data from a different year. If, on the other hand, if the cloud properties during other years differ from those seen in 1992 the average biases computed in Table 1 will increase or decrease correspondingly.

If clouds during a given year are of different optical thickness than those seen during 1992, there will be a corresponding change in the scattering-induced delay as well. There is, however, no record of variations in optical thickness from one year to another. Absent this information, we must assume the optical properties of the increased (or reduced) cloud occurrence, to obtain the bounds of the interannual variability in bias. We can assume, for instance, that any increases (or decreases) in cloud occurrence relate only to optically thin (or alternately, thick) clouds, thereby obtaining the minimum and maximum variability of the bias. By thus removing (or adding) the clouds with the most and least impact on altitude biases from the 1992 data along with the known variability in cloud occurrence (5% in summer, 11% in winter), we can obtain new annual average bias values.

The altitude biases obtained by considering such differences from the optical depths seen in 1992 are tabulated in Table 1. As is expected, the addition of thick clouds increases the values of the seasonal and annual altitude biases, as does the removal of thin clouds. Conversely, the addition of thin clouds, or the removal of thick clouds, reduces the average altitude bias. The interannual variability seen from such increased or reduced cloud occurrence is high; the change in the annual average altitude bias from 1992 (last column of the table) is larger than the GLAS mission's specified limit for the relative bias between years (1.5 cm).

A second calculation can also be made using the maximum reported interannual variability in cloud occurrence (13% in summer, 27% in winter) instead of the average values, also from Hahn *et al.*'s measurements. As was done in obtaining values for Table 1, in this case too, the additional (or fewer) clouds are viewed to be entirely of the extreme optical depth regimes, and the annual average biases in the altitude are computed again; these numbers are shown in Table 2. As one would expected, the seasonal and annual values of variability in bias are now even more different from the 1992 numbers, up to three or four times the GLAS mission specification.

These numbers suggest that the variation in cloud occurrence and optical thickness from one year to another produces variation in the altitude bias that is significant. The values of such variability, being comparable to or greater than the GLAS mission specification, will clearly impede the reliable determination of altitude changes from one year to the next. Indeed, the most advantageous of the various changes considered in Tables 1 and 2 still produces interannual bias variations of 1 to 1.5 cm.

Similar assessments can also be made with changes in particle sizes instead of or in addition to optical depth changes. The results in Table 1 and 2 implicitly assume that whereas optical depths from one year to another are different, the particle sizes and optical depths are comparable between the two years. The potential impact of changes in those characteristics cannot be overlooked. However, our intention here is to suggest that variability in cloud occurrence can manifest itself in significant variations in the altitude bias of GLAS measurements from one year to another. Without quantifying the potential impact on altitude bias from every conceivable change in cloud characteristics, we have attempted to define some range of values to such variability. This effort shows that variation in the altitude bias could be of the same magnitude as or larger than the accuracy requirement specified for the GLAS mission itself. The determination of surface altitudes, already uncertain due to the presence of clouds, must additionally be reconciled with year-to-year changes in the uncertainty in such measurements.

3.2.2. Variability from synoptic reports

In Section 3.2.1, we obtained the interannual variability in the altitude bias due to variation in cloud occurrence from one year to the next; in this section we determine the variability that would result from variations in the cloud fractions. Whereas cloud occurrence the mere presence or absence of clouds, the cloud fraction contains additional information - it is the portion of the sky from each observation that is filled by clouds. The multiple-scattering induced delay results not only from variation in cloud occurrence, which we examined in the previous sub-section, but just as likely from changes in fractional cloud cover from one year to the next. An alternate approach to obtaining the interannual variability in the altitude bias is to use fractional cloud cover information reported by surface observers on a regular basis, and to assume no variability in cloud occurrence, optical depths, or particle sizes.

The routine surface observations and synoptic reports that contain cloud cover data, in contrast to the ones of Mahesh *et al*., are made visually and without the advantage of reference heights in the uniform topography around South Pole station; this precludes the accurate knowledge of cloud heights. However, unlike the spectral measurements, the visual observations are not limited to a particular line of sight. For this reason, the multi-year visual observations provide a useful dataset that describes typical sky-cover conditions at South Pole.

From the WMO synoptic data taken at South Pole station, values of fractional cloud cover, as well as the variability in those values, were obtained separately for the winter and non-winter months of the years 1992-94. The average cloud cover fraction for the three year period around the 1992 data was 42% during the winter months, and 52% during the other months. Inter-annual variability in these values (as measured by the standard deviation) is slightly larger (11.5%) in the winter than in the rest of the year (8.1%). Using the seasonal average altitude biases obtained in Section

3.1, the corresponding increases or decreases that would result from changes in cloud fractions can be computed. The variations in cloud cover fractions correspond to variation in the interannual bias of 0.75 cm during the winter months, and 0.85 cm during the rest of the year; this results in an average interannual variability in the bias of approximately 0.8 cm.

These numbers are lower than the values we saw in section 3.2.1; this is expected, since in this case we have distributed the variability across clouds of all optical depths. Very (optically) thin and thick clouds represent the extremes at which the ranging delay is least and largest respectively, and the average of changes at these extremes is expected to be larger than when variations are considered to be manifest across clouds of all optical thicknesses.

3.3. Methods to reduce bias

The results presented so far assume the altimetry measurements will be used as a "stand-alone" measurement, with no information available on cloud properties. However, if the optical depths of the clouds under observation were known, then we could select those instances when the optical depths are small enough that the altimetry errors expected from them are small. Multiple-scattering effects from clouds, which cause altimetry biases, will understandably be smaller when subsets of observations are chosen eliminating highly scattering layers. We began our discussions of cloud-scattering effects using all clouds, however, because in the absence of climatologies for optically thin clouds, the total cloud cover data is still useful. First, they are the only available estimates of interannual variability. Also, it is the only way of relating cloud statistics from the interior of the plateau to those from the coastal Antarctic or the Arctic. Although it is possible that seasonal/interannual variability of thin clouds does not match the variability of the total cloud distribution, we saw (in the previous section) that it can provide useful boundaries to variability.

We now turn our attention to subsets of observations that include only optically thin clouds or cloud-free conditions. The use of data from the cloud and aerosol profiling channel on GLAS can provide the necessary information to obtain such selective data. Cloud optical depths can be obtained from the green channel if clouds are sufficiently thin so that a lidar signal is detectable both above and below them [16]. The limiting optical depth for such analysis is between 1 and 2, and a substantial fraction of Antarctic clouds are transmissive enough to permit such a determination of layer optical depth.

Using optical depths so determined, the altitude bias could then be reduced by setting a cloud optical depth threshold for acceptable GLAS observations. Additionally, biases could be reduced by using a more sophisticated method to analyze the lidar surface returns. Both approaches are discussed below.

From the entire set of observations, subsets can be selected using lower optical depth thresholds. Table 3 shows the seasonal and annual values of the altitude biases obtained using several different thresholds - 0.1, 0.5, 1.0 and 2.0 - along with the numbers from all observations. Since very few clouds at South Pole (approximately 10-15%) have optical depths larger than 2, the bias obtained with the cloud optical depth threshold set to 2 is not significantly different from the bias obtained from all the data. However, as the optical depth threshold is lowered, the altitude bias drops correspondingly. The values in altitude bias obtained at the lowest threshold shown (0.1) approach the GLAS requirements to detect secular changes in ice thickness as small as 1.5 cm a year. Limiting the computation of altitude bias to such cloud-free or nearly cloud-free observations also largely removes the interannual variability in altitude bias.

An alternate approach to limiting the bias in estimated altitudes is to use a more sophisticated algorithm to analyze the GLAS measurements. The Gaussian fit method described in paper 1 (DSE), for example, eliminates a significant fraction of the scattering-induced delay. Table 4 shows calculations of scattering-induced delays obtained from this method; this table is readily comparable to Table 3. The median altitude bias obtained with this fit is nearly 40% smaller in winter, and one-third smaller during the other months; the mean values are reduced by even greater amounts. At very low optical depths, the altitude bias averaged over the entire year is less than 1.5 cm.

3.4. Observations under blowing snow conditions

As discussed above, the altitude bias can be held to small values if we selectively exclude observations that include clouds of relatively large optical depths. It will be especially advantageous, in fact, to limit the determination of altitude to those observations which are made under known cloud-free conditions. The use of the atmospheric channel on GLAS will permit such a determination, so that the 1064 nm channel is not used as a stand-alone observation. There is, however, an additional concern, namely blowing snow.

Throughout much of the Antarctic plateau, downslope surface winds known as katabatic winds are prevalent during much of the year. The settling of cold air at the higher elevations of the plateau creates these surface winds, which can disturb loose and recent snow. Visual observations made by the surface weather observers at South Pole station indicate blowing snow conditions in up to a third of all observations [17]. Blowing snow is typically not very optically thick, and spectral measurements used in Mahesh *et al*. suggest that an optical depth of 0.1 is as thick as the snow may be.

The concern for GLAS, however, is not just the optical depth of the snow, but its proximity to the surface. Blowing snow typically extends from the surface up to the lowest 50-300 meters, and a special operational mode to process GLAS data at 50-m resolution is needed to detect these thin near-surface layers. When a scattering layer is close to the surface photons scattered by it nevertheless remain within the footprint of the GLAS measurement. As a result, the delay in their travel times caused by such scattering becomes included in altimetry calculations. This means that even if GLAS altimetry is limited to nearly or entirely cloud-free conditions as determined using the 532 nm channel, the altitude values obtained from them might be in error.

Using a typical value (100 microns) for the snow particle radius, and several combinations of physical and optical thicknesses for the blowing snow layer, Monte Carlo calculations were performed as before to obtain an estimate of the altitude bias due to blowing snow. Figure 4 shows the altitude bias due to blowing snow for two different optical depths (filled circles and squares) at several different physical thickness values for the snow layer. Also shown are the lower bias estimates obtained when the calculations are repeated with the Gaussian fit (corresponding open circles and squares) described in DSE. A blowing snow layer 50-100 m thick with an optical depth between 0.05 and 0.1 will bias the altitudes derived by between 2 and 4 cm approximately; this bias can be considerably reduced (to between 0.5 and 1.0 cm) by the use of the Gaussian fit method to determine the centroid of the return pulse.

4. Summary and Conclusions

Atmospheric multiple scattering is potentially a large error source for precision laser measurements of surface altitude as envisioned for the Geoscience Laser Altimeter System (GLAS) or other similar space missions. Also, a survey of polar cloud observations indicates that most of the cloud properties that will affect spaceborne lidar measurements have significant seasonal and interannual variations. Using a recently completed study of Antarctic cloud properties, the potential impact of such clouds on GLAS altitude measurements is quantified. The likely inter-annual variability in altitude bias that will result from year-to-year variation in the relevant cloud properties is also determined. These calculations suggest that the atmospheric scattering effects on GLAS measurements are not insignificant.

Using cloud properties derived from observations made at the South Pole as well as the path delay data from DSE, estimates of the mean Antarctic summer and winter altitude bias were computed. From the interannual variability in cloud occurrence and cloud fraction estimated by surface visual observers, the likely year-to-year variation in the altitude bias was also obtained. The bias in altitude introduced by clouds in the path of the lidar pulse appears to be significant, and is often larger than the accuracies specified for the mission. Further, interannual variability in the bias itself is substantial; and a uniform altitude bias cannot be subtracted out of observations made.

However, altimetry measurements can be confined to those observations made from the satellite which are known to be under cloud-free or optically thin-cloud conditions; this reduces the altitude biases a great deal. To overcome the limitations in altimetry measurements caused by the bias resulting from scattering within cloud layers, ice sheet elevations should thus be determined only from cloud-free observations. This can be achieved using the atmospheric channel at 532 nm for cloud-detection, alongside the 1064 nm channel's altimetry capability. The use of improved waveform analysis techniques, more sophisticated than merely accepted the centroid of return pulses, can further reduce the biases.

Even with the selective use of clear-sky conditions for altimetry calculations, near-surface blowing snow which occurs frequently will remain unaccounted for. The proximity of the snow to the surface makes this scattering layer more potent (per unit optical depth) than clouds, since scattered, delayed photons remain within the field of view of the instrument. An altitude bias of 1-3 cm from the snow layer alone is likely. However, as with clouds, the use of improved methods to analyze the return pulse will help in substantially reducing the bias under blowing snow conditions.

The upcoming GLAS mission, by monitoring ice-sheet altitude changes over Antarctica and elsewhere, is expected to provide information on whether global warming is affecting a sensitive and important part of the planet. Potential melting of high-latitude ice sheets from warming will likely lead to significant rises in sea level, and consequently to catastrophic outcomes along coastlines around the world and in many island nations. This paper suggests that the measurement accuracies necessary to permit the required monitoring are achievable under conditions of thin or no cloud cover. Careful selection of data from which GLAS altimetry measurements are made is therefore necessary to ensure that ranging delay due to scattering is accounted or corrected for.

A factor that has not been included in this analysis is the effect of surface slope on the altitude bias. The results of DSE suggest that sloped surfaces may obscure the effects of cloud multiple scattering on the path delay, and make the determination of the return pulse centroid more difficult. In addition, other factors such as signal noise and surface roughness have not been examined. These factors may also reduce the effectiveness of Gaussian fitting on the path delay, and other forms of return pulse analysis may be required to reduce altimetry biases to acceptable levels. Further study is necessary to determine how signal noise, rough, sloped surfaces and advanced waveform analysis of the return pulse may affect the multiple scattering-induced altitude bias.

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REFERENCES

[1] Vaughan, D. G., and C. S. M. Doake, Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. *Nature*, **379**, 328-331, 1996.

[2] S. Cohen, J. Degnan, J. Bufton, J. Garvin, and J. Abshire, The geoscience laser altimetry/ranging system, *IEEE Trans. Geoscience Remote Sensing*, **GE-25**, pp. 581--592, 1987.

[3] W. Krabill, R. Thomas, K. Jezek, K. Kuivinen, and S. Manizade, Greenland ice sheet thickness changes measured by laser altimetry. *Geophys. Res. Lett*., **22**, 2341--2344, 1995.

[4] H. J. Zwally, A. C. Brenner, J. A. Major, R. A. Bindschadler, and J. G. Marsh, Growth of the Greenland ice sheet: Measurement, *Science*, **246**, 1587--1589, 1989.

[5] H. J. Zwally, B. Schutz, W. Abdalati, J. Abshire, C. Bentley, A. Brenner, J. Bufton, J. Dezio, D. Hancock, D. Harding, T. Herring, B. Minster, K. Quinn, , S. Palm, J. Spinhirne, and R. Thomas, ICESat's Laser Measurements of Polar Ice, Atmosphere, Ocean, and Land. Submitted to the *J. Geodynamics*, 2001.

[6] D. P. Duda, J. D. Spinhirne, and E. W. Eloranta, Atmospheric multiple scattering effects on GLAS altimetry. Part I: Calculations of single pulse bias," *IEEE Trans. Geoscience Remote Sensing*, vol. **39**, pp. 92-101, 2001.

[7] C. Hahn, S. Warren, and J. London, "Climatological data for clouds over the globe from surface observations, 1982-1991: Data tape documentation for the total cloud edition," Numerical data package NDP-026A, Available from Carbon Dioxide Information Analysis Center, Oak Ridge National Lab, 1995.

[8] J. A. Curry, W. B. Rossow, D. Randall, and J. L. Schramm, "Overview of Arctic cloud and radiation characteristics," *J. Clim*., vol. **9**, pp. 1731-1764, 1996.

[9] Japan Meteorological Agency, "Climatological data at Syowa station, Antarctica," *Antarct. Rec.*, vol. **73**, pp. 273-303, 1981.

[10] A. Mahesh, V. P. Walden, and S. Warren, "Ground-based remote sensing of cloud properties over the Antarctic Plateau. Part I: Cloud Base Heights.", *Journal of Applied Meteorology*, vol. **40**, pp. 1265-1278, 2001.

[11] A. Mahesh, V. P. Walden, and S. Warren, "Ground-based remote sensing of cloud properties over the Antarctic Plateau. Part II: Cloud Optical Depths and Particle Sizes", *Journal of Applied Meteorology*, vol. **40**, pp. 1279-1294, 2001.

[12] L. D. Wilson, J. A. Curry, and T. P. Ackerman, "Satellite retrieval of lower-tropospheric ice crystal clouds in the polar regions," *J. Climate*, vol. **6**, pp. 1467-1472, 1993.

[13] V. N. Smiley, B.M.Whitcomb, B. M. Morley, and J. A. Warburton, "Lidar determinations of atmospheric ice crystal layers at South Pole during clear-sky precipitation," *J. Appl. Meteor.*, vol. **19**, pp. 1074-1090, 1980.

[14] R. S. Stone, "Properties of austral winter clouds derived from radiometric profiles at the South Pole," *J. Geophys. Res.*, vol. **98**, pp. 12,961-12,971, 1993.

[15] D. Lubin, and D. A. Harper, "Cloud radiative properties over the South Pole from AVHRR infrared data." *J. Climate*, vol. **9**, pp. 3405-3418, 1996.

[16] S. P. Palm, W. Hart, D. L. Hlavka, E. J. Welton, and J. D. Spinhirne, "Geoscience Laser Altimeter System (GLAS), Algorithm Theoretical Basis Document, Version 4.1." Available from Code 912, Goddard Space Flight Center, Greenbelt MD 20771, 2001.

[17] V. P. Walden, and S. G. Warren, "A spectral downward longwave climatology for clear and cloudy skies over South Pole," IRS '96: *Current Problems in Atmospheric Radiation*, W. L. Smith and K. Stammes, Eds., A. Deepak Publishing, Hampton, VA, pp: 54-57, 1996.

List of Figures

Figure 1. Mean annual cloud occurrence over the Arctic derived from [6].

Figure 2. Histogram of scattering-induced altimetry errors obtained by Monte Carlo calculations, using cloud properties obtained from interferometer measurements made during 1992. The upper panel (a) includes observations of both clear-sky as well as cloudy conditions; scattering-induced delay under clear sky conditions is assumed to be zero. In the lower panel, only the cloudy cases are considered separately. The median value of the scattering induced bias from only the cloudy-sky observatrions is 10.8 cm.

Figure 3. Multiple-scattering induced altitude bias from all observations of clouds during 1992, obtained by Monte Carlo calculations. The pluses (+) represent data when both cloud optical depth and particle radius are known. In other cases, only a lower limit to the scattering induced delay is calculable, either because only a lower limit to the optical depth is known (diamonds), or only a lower limit to the particle effective radius is known (open circles), or both (filled circles).

Figure 4. Scattering-induced altitude bias from blowing snow. Results are shown for two different optical depths, using both the centroid of the return pulse, as well as the Gaussian fit discussed in DSE. The filled circles are at an optical depth of 0.1 and the filled squares at an optical depth of 0.05; each of these were obtained from the centroid of the return pulse. The corresponding values obtained from the Gaussian fit at the two optical depths, are shown as open circles and squares respectively.

Table 1: Altitude bias values, and changes in those values from 1992 annual and seasonal averages, assuming that *average* year-to-year variation in cloud occurrence (5% in the summer, 11% in the winter) is contained entirely in either thick (τ>2) clouds or in thin (τ<2) clouds.

	More clouds than in 1992		**Fewer clouds than in 1992**		**Average variability from 1992**
	thick	**thin**	**thick**	**thin**	
summer	23.04	20.39	19.40	22.33	1.37
winter	17.40	13.33	11.05	16.13	2.29
all-year	18.41	15.13	13.56	17.42	1.78

Table 2: Altitude bias values, and changes in those values from 1992 annual and seasonal averages, assuming that *extreme* year-to-year variation in cloud occurrence (13% in the summer, 27% in the winter) is contained entirely in either thick (τ>2) clouds or in thin (τ<2) clouds.

	More clouds than in 1992		Fewer clouds than in 1992		Average variability from 1992
	thick	thin	thick	thin	
summer	25.48	19.08	15.89	24.20	3.68
winter	20.65	11.90	4.01	19.23	5.99
all-year	21.20	13.82	8.66	19.73	4.61

Table 3: Seasonal and annual average values of multiple-scattering induced bias in surface elevation at South Pole, for several subsets of the measurements from 1992. The subsets are chosen using varying optical depth thresholds; as thicker clouds are excluded from consideration, the scattering-induced delay becomes smaller.

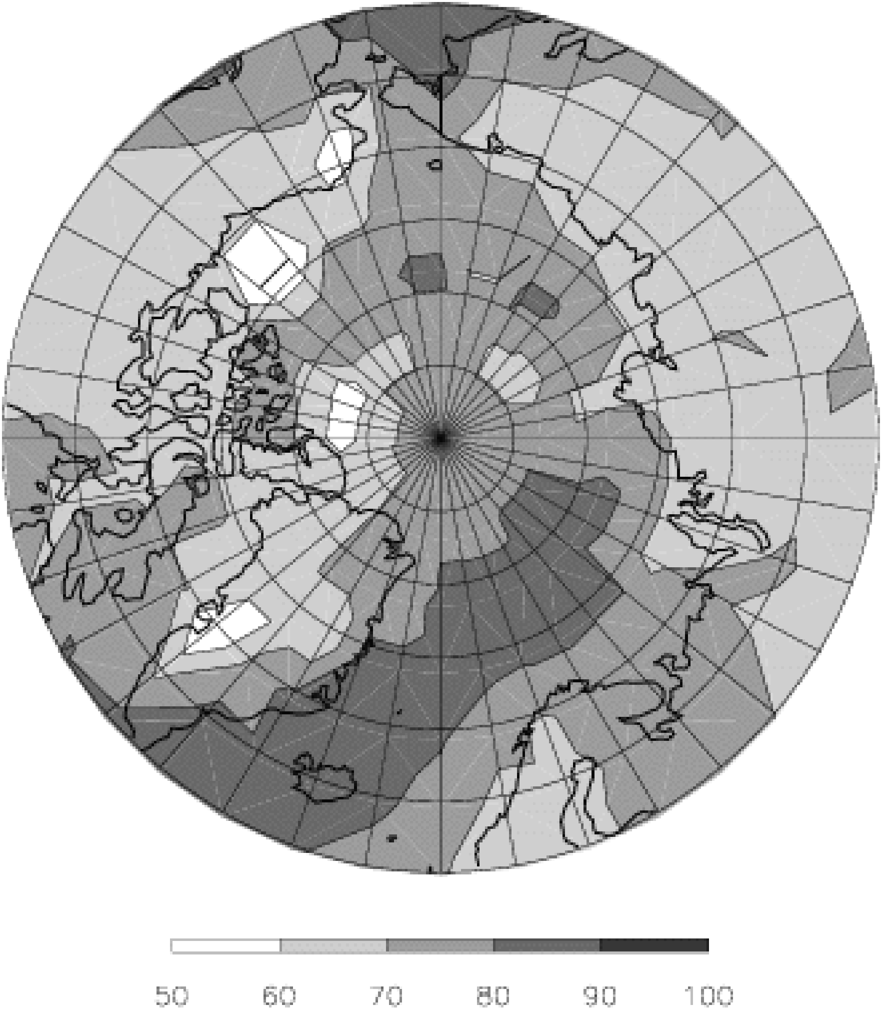
	WINTER (April-September)		**NON-WINTER** (October-March)		**All year** (1992)	
	Median	**Mean**	**Median**	**Mean**	**Median**	**Mean**
all clouds	8.66	14.57	14.46	21.31	10.82	16.18
$\tau < 2$	7.05	9.73	13.91	15.97	8.76	11.25
$\tau < 1$	5.29	6.46	10.49	10.79	5.97	7.25
$\tau < 0.5$	4.12	4.67	5.48	6.29	4.15	4.87
$\tau < 0.1^{*}$	1.89	2.00	1.94	1.97	1.89	2.00

*Between October and March, i.e. during the non-winter months, no clouds were observed with optical depths smaller than 0.1, the values listed in the table are from the thinnest cloud observed during that period, on October 5, 1992, with optical depth 0.16.

Table 4: Identical to Table 3, except that the multiple-scattering induced biases were obtained in this case using the Gaussian fit method described in DSE**.**

	WINTER (April-September)		**NON-WINTER** (October-March)		**All-Year** (1992)	
	Median	**Mean**	**Median**	**Mean**	**Median**	**Mean**
all clouds	5.03	6.55	9.51	10.45	5.64	7.50
$\tau < 2.0$	3.85	4.76	9.17	8.42	5.03	5.65
$\tau < 1.0$	3.09	3.62	5.45	5.67	3.29	3.99
$\tau < 0.5$	2.49	2.75	3.14	3.48	2.53	2.85
$\tau < 0.1^{*}$	1.19	1.22	1.71	1.71	1.19	1.22

* Between October and March, i.e. during the non-winter months, no clouds were observed with optical depths smaller than 0.1, the values listed in the table are from the thinnest cloud observed during that period, on October 5, 1992, with optical depth 0.16.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70
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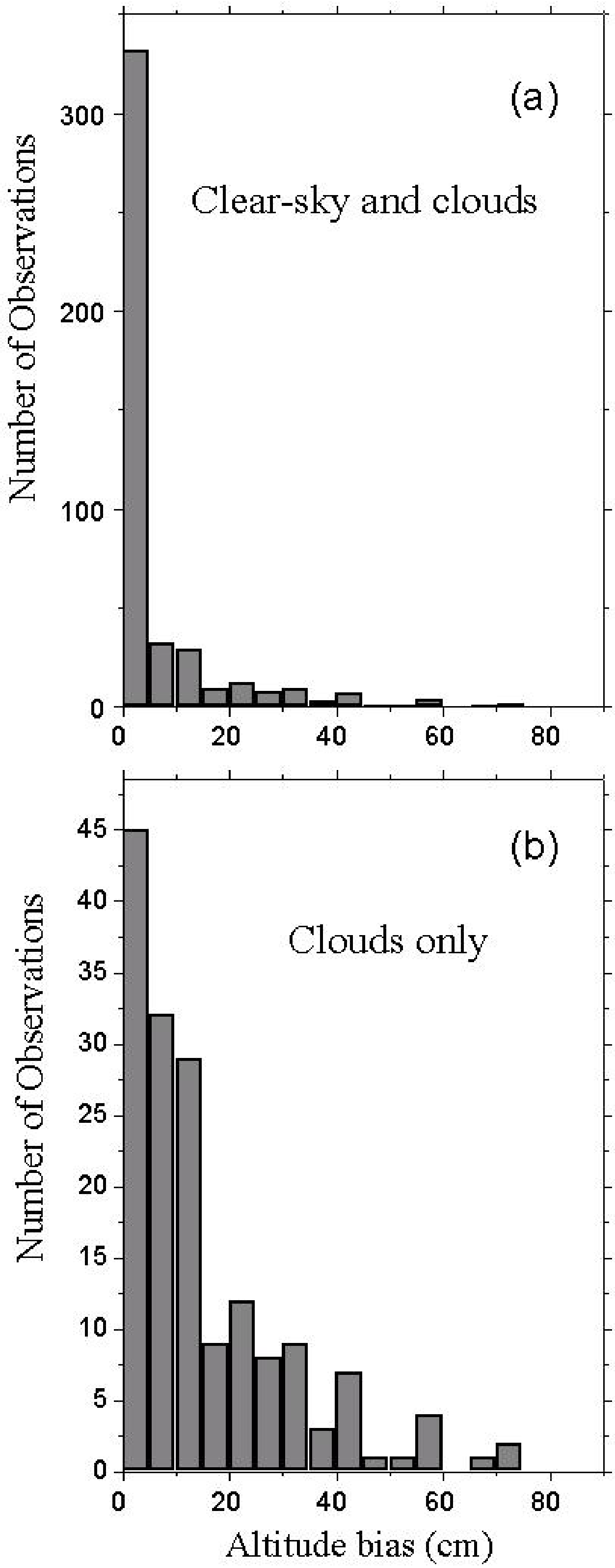
(a)
Clear-sky and clouds
Number of Observations
0
100
200
300
0
20
40
60
80
(b)
Clouds only
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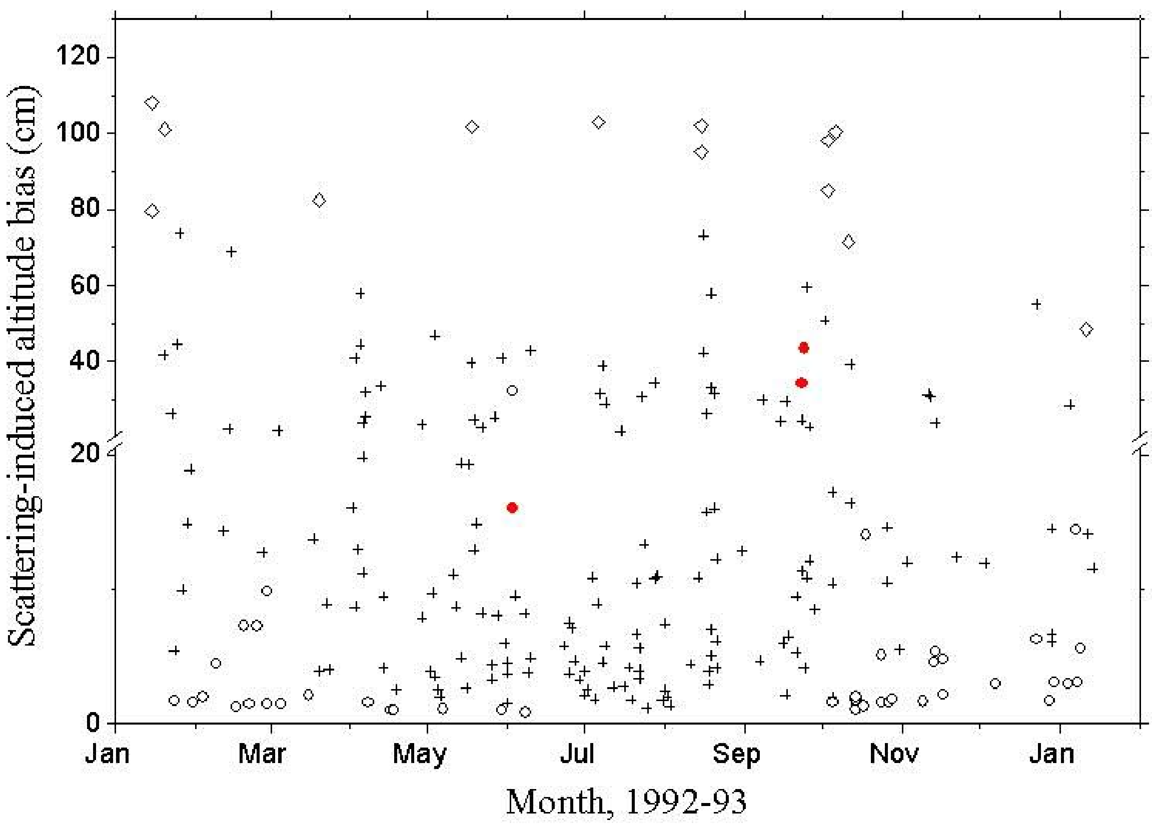
10
15
20
25
30
35
40
45
0
20
40
60
80
Altitude bias (cm)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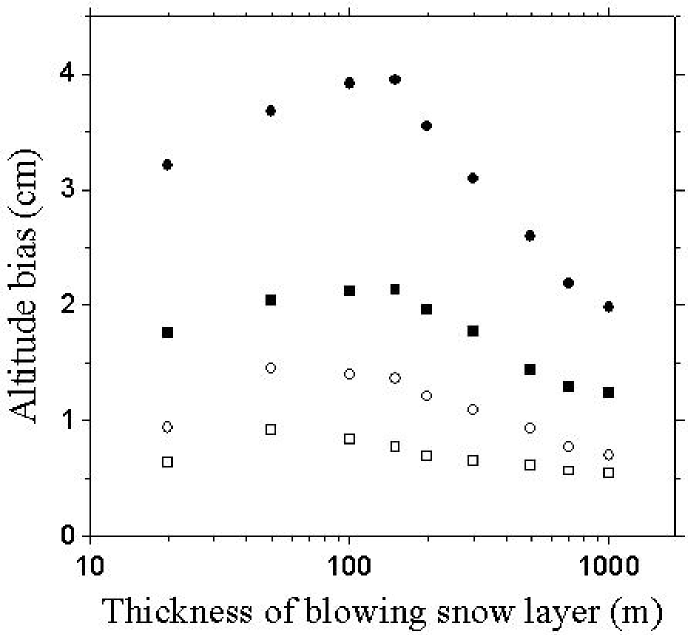
40
60
80
100
120
Jan
Mar
May
Jul
Sep
Nov
Jan
Month, 1992-93


Altitude bias (cm)
0
1
2
3
4
10
100
1000
Thickness of blowing snow layer (m)